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GB A 2125161 WO A1 79/00377 US 4436995
EP A2 0027540

(58) Field of search
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G2F
Selected US specifications from IPC sub-classes G01B G01L G01N

(54) Strain gauges

(57) A microbend fibre optic strain gauge comprises a pair of plates 12, 14 having facing offset corrugations 16, 18 which clamp a signal optical fibre 10 therebetween. The optical fibre 10 is coated and a light signal is supplied to one end of the fibre and read at an opposite end of the fibre by an optical sensor. Modulations in the light are primarily due to a difference in pressure being applied to the fibre 10 by the plates 12, 14. The gauge may include a reference optical fibre (11—Fig. 2) which is near the signal optical fibre 10 and is subjected to the same thermal condition, a light signal thereof being compared to the light signal from the signal optical fibre to offset any temperature error introduced into the signal by changes in temperature. Aluminium, polyimide or gold coating increases the temperature resistance of the fibres.

FIG. 1

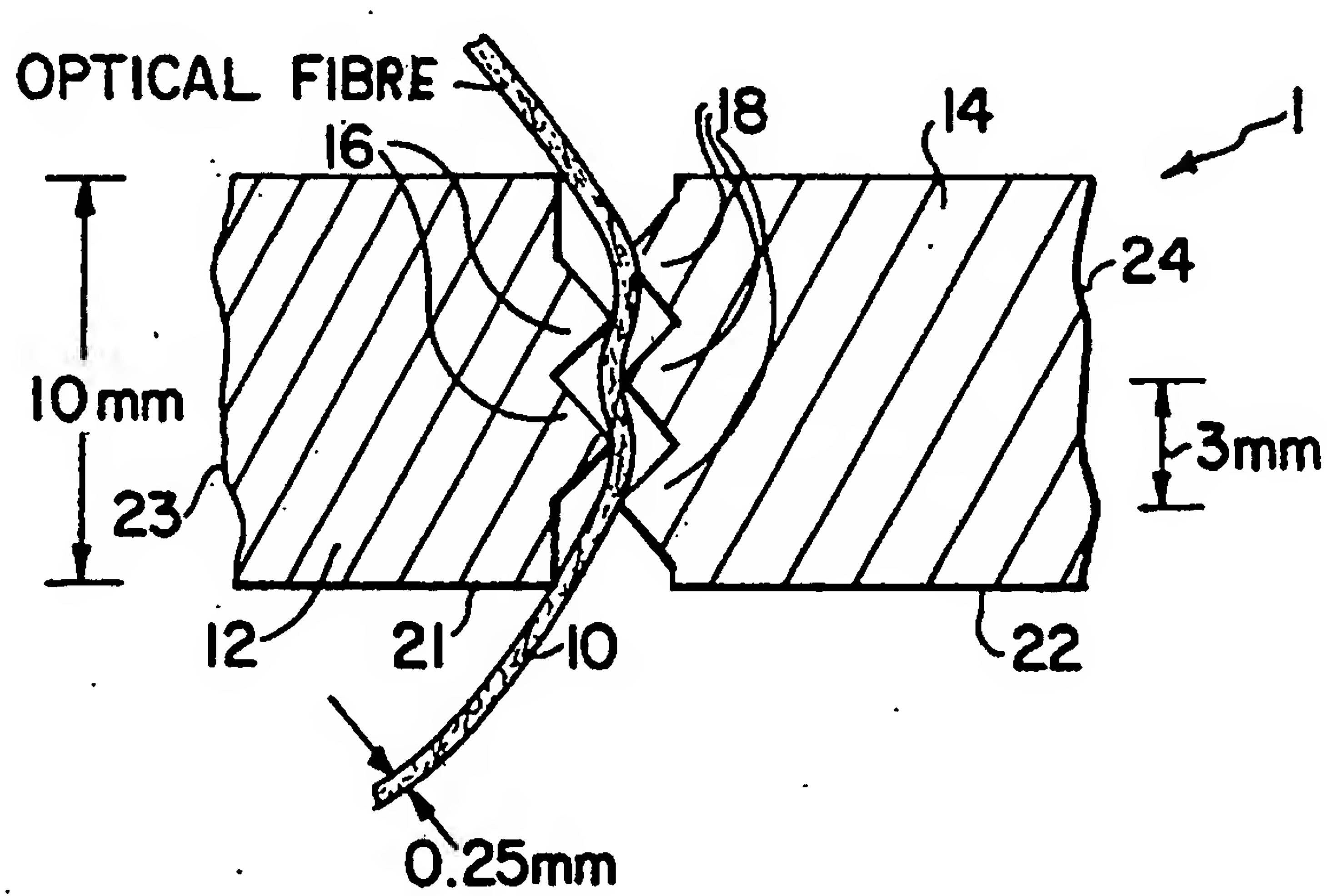

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FIG. 1

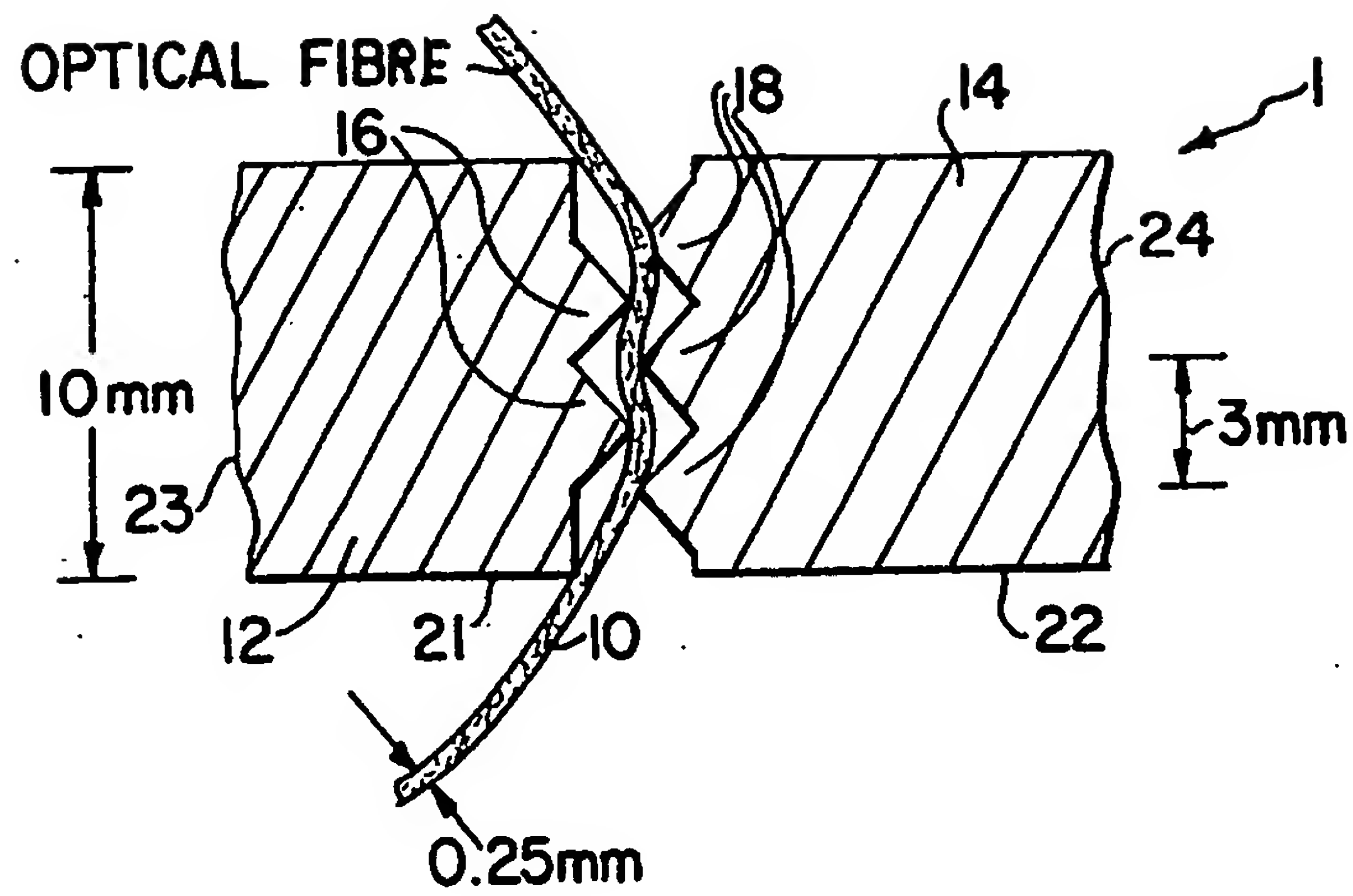

OPTICAL FIBRE
16
18
14
1
24
10mm
3mm
23
12
21
10
22
0.25mm

FIG. 2

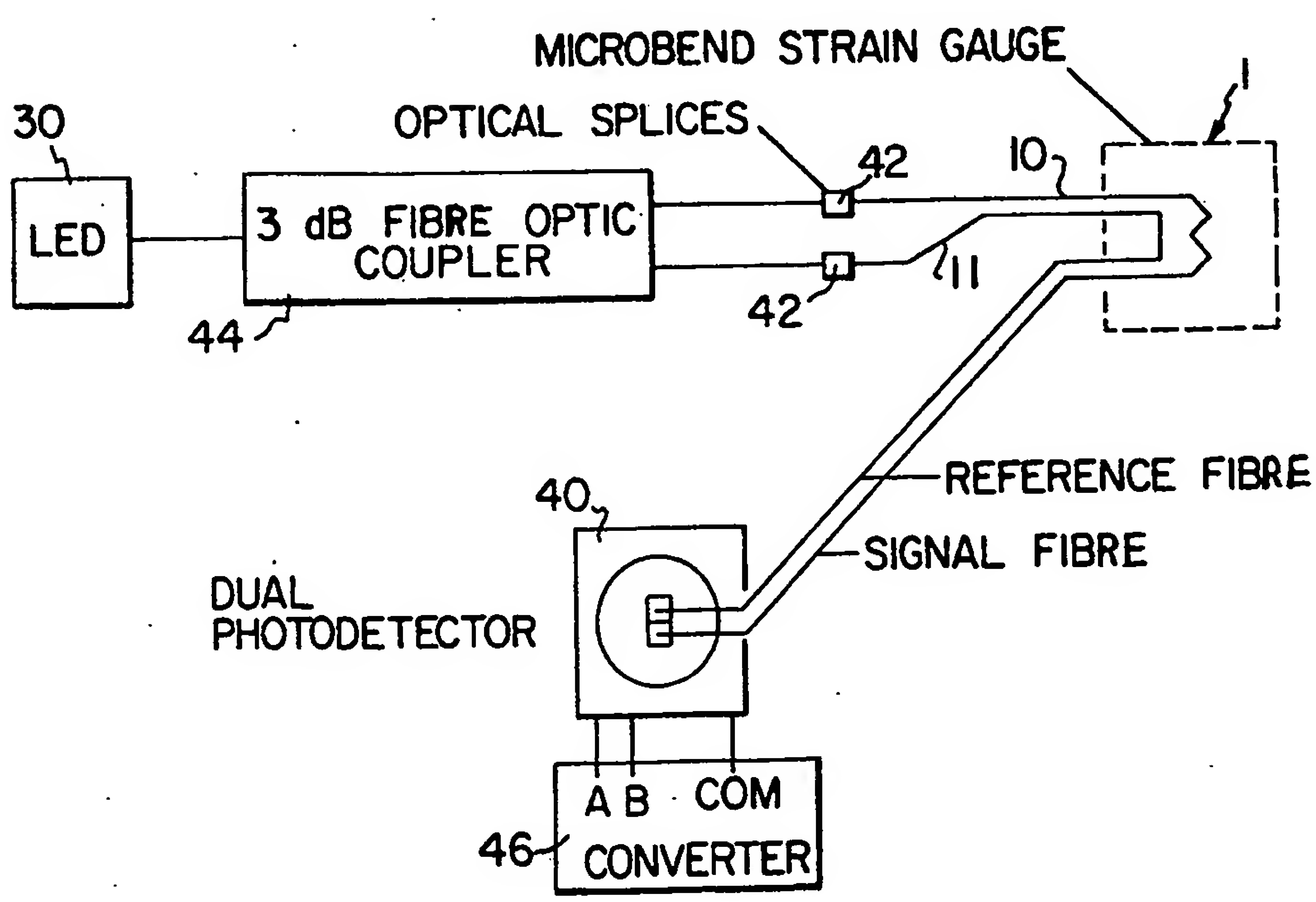

MICROBEND STRAIN GAUGE
1
30
OPTICAL SPLICES
42
10
LED
3 dB FIBRE OPTIC COUPLER
11
42
44
REFERENCE FIBRE
40
SIGNAL FIBRE
DUAL PHOTODETECTOR
A B COM
46
CONVERTER

FIG. 3

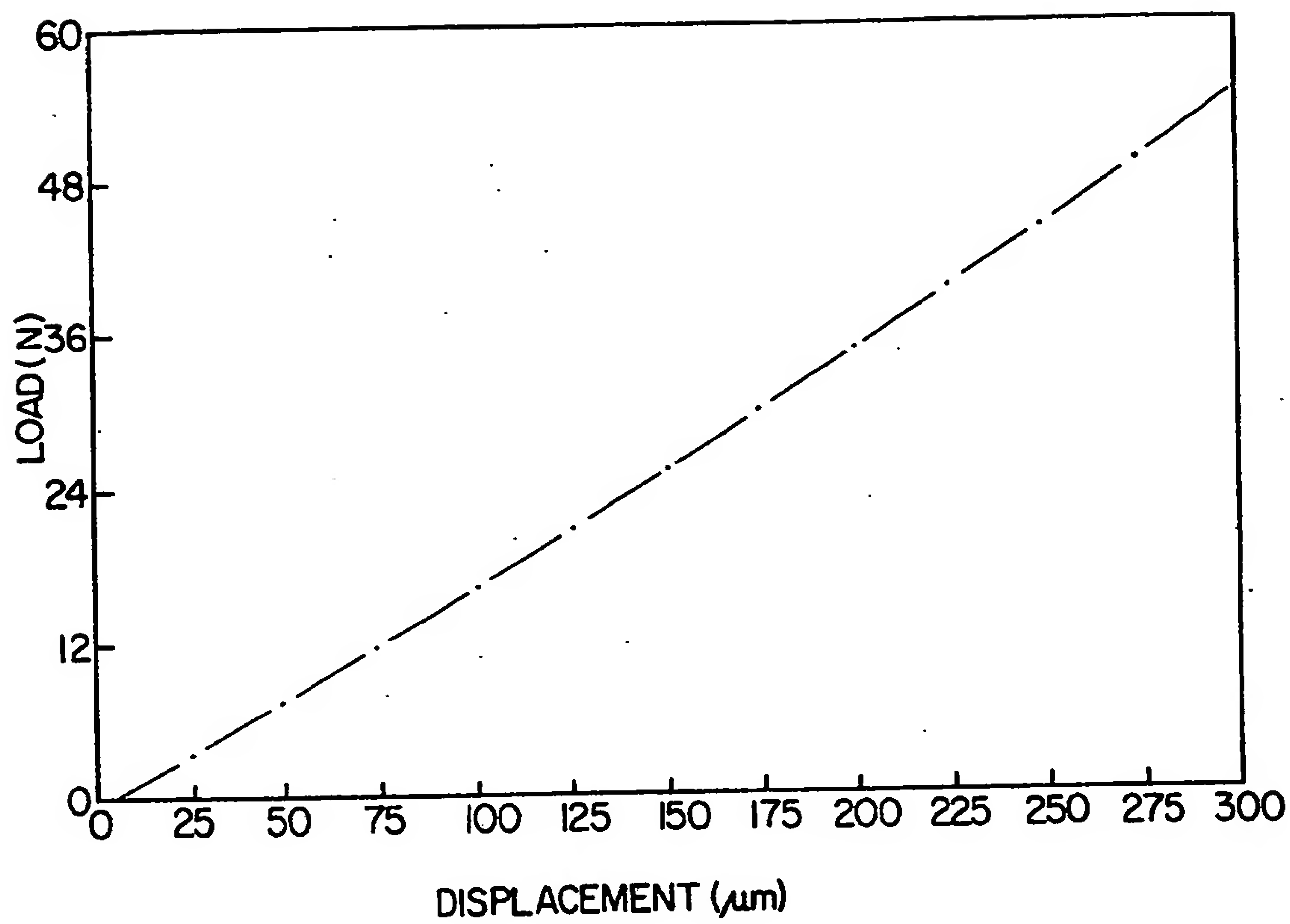
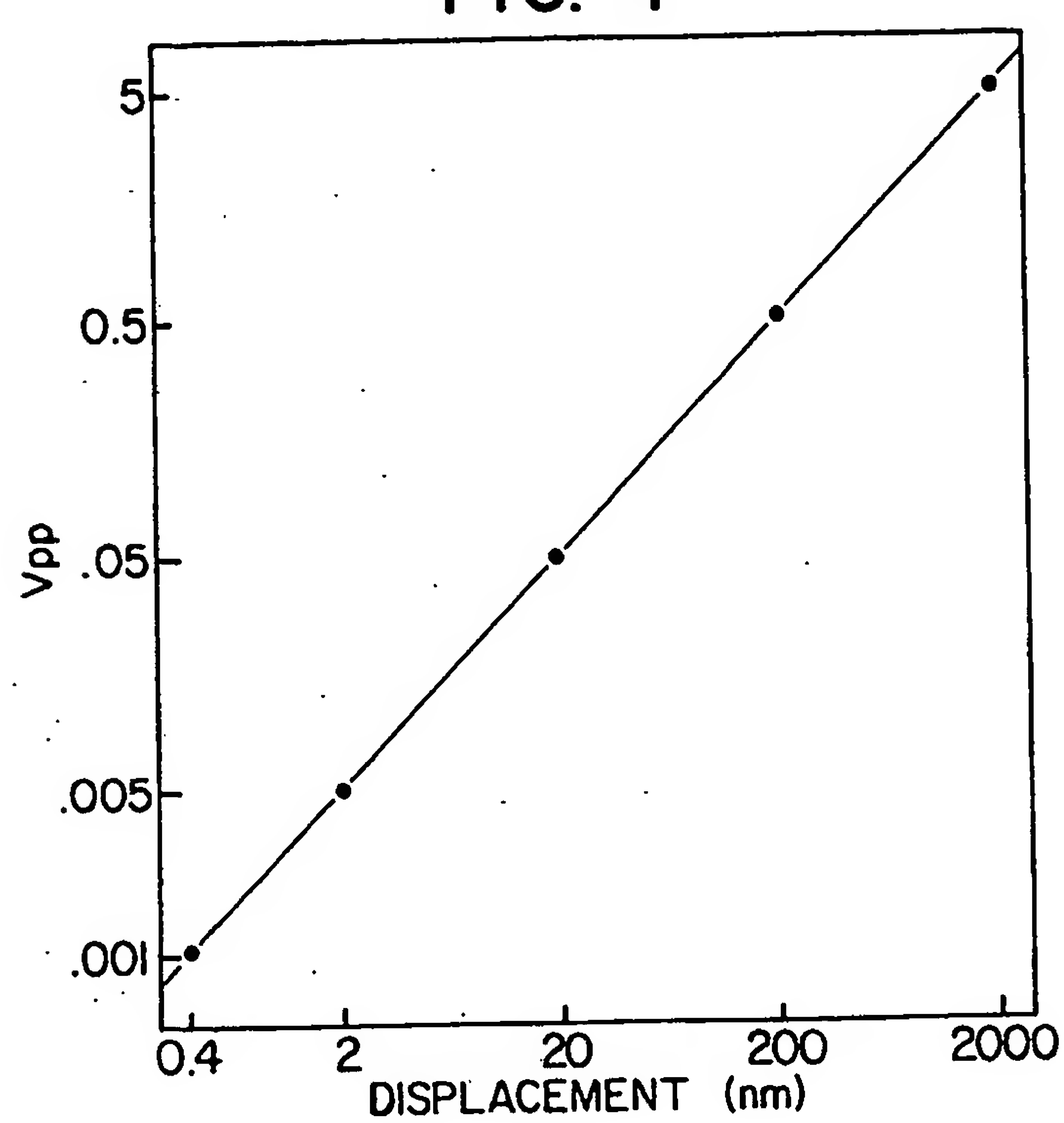

60
48
36
24
12
0
LOAD (N)
0
25
50
75
100
125
150
175
200
225
250
275
300
DISPLACEMENT (μm)

FIG. 4


5
0.5
.05
.005
.001
Vpp
0.4
2
20
200
2000
DISPLACEMENT (nm)

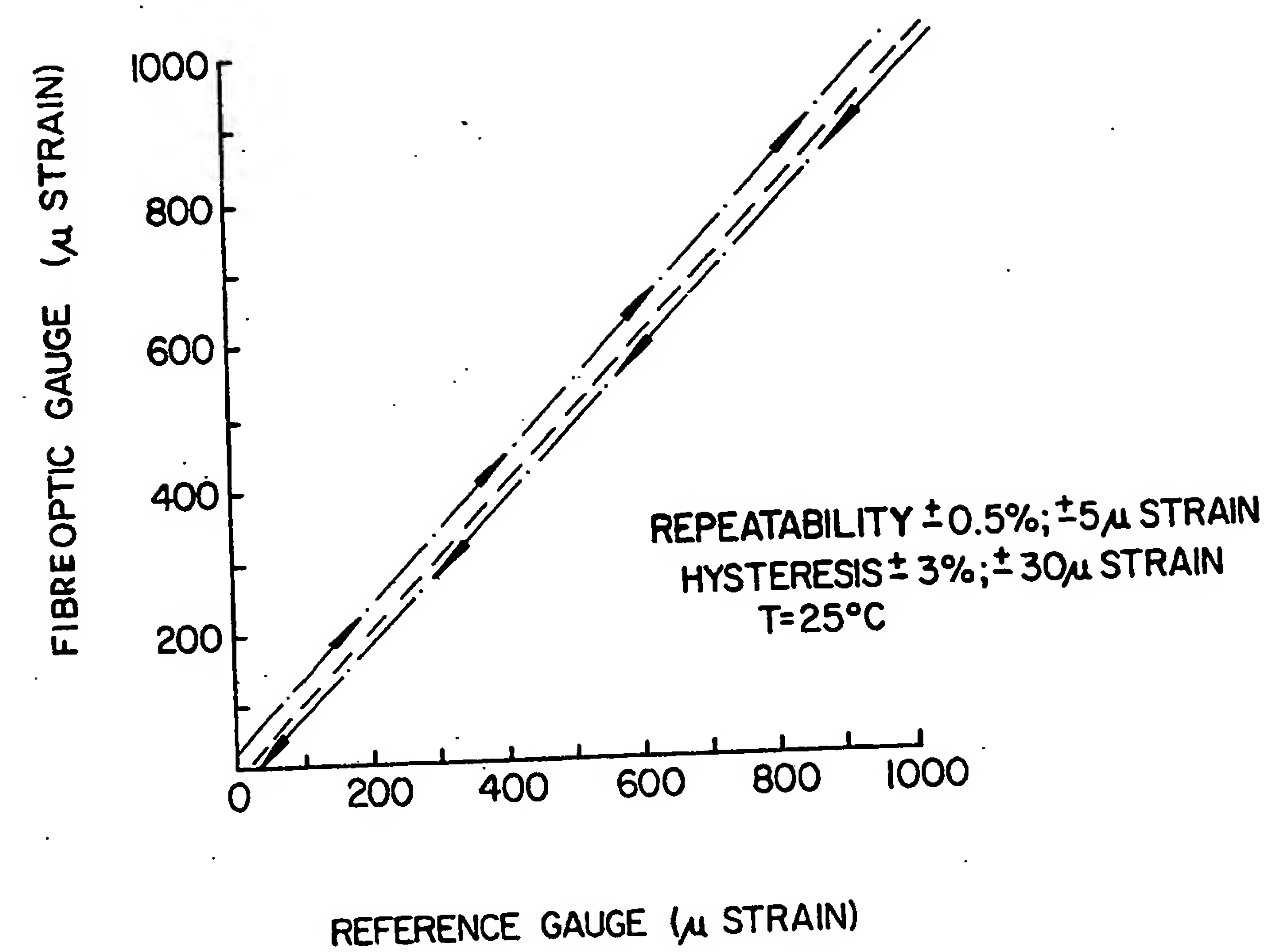

FIBREOPTIC GAUGE (μ STRAIN)
1000
800
600
400
200
0
200
400
600
800
1000
REPEATABILITY ±0.5%; ±5μ STRAIN
HYSTERESIS ± 3%; ± 30μ STRAIN
T=25°C
REFERENCE GAUGE (μ STRAIN)

FIG. 5

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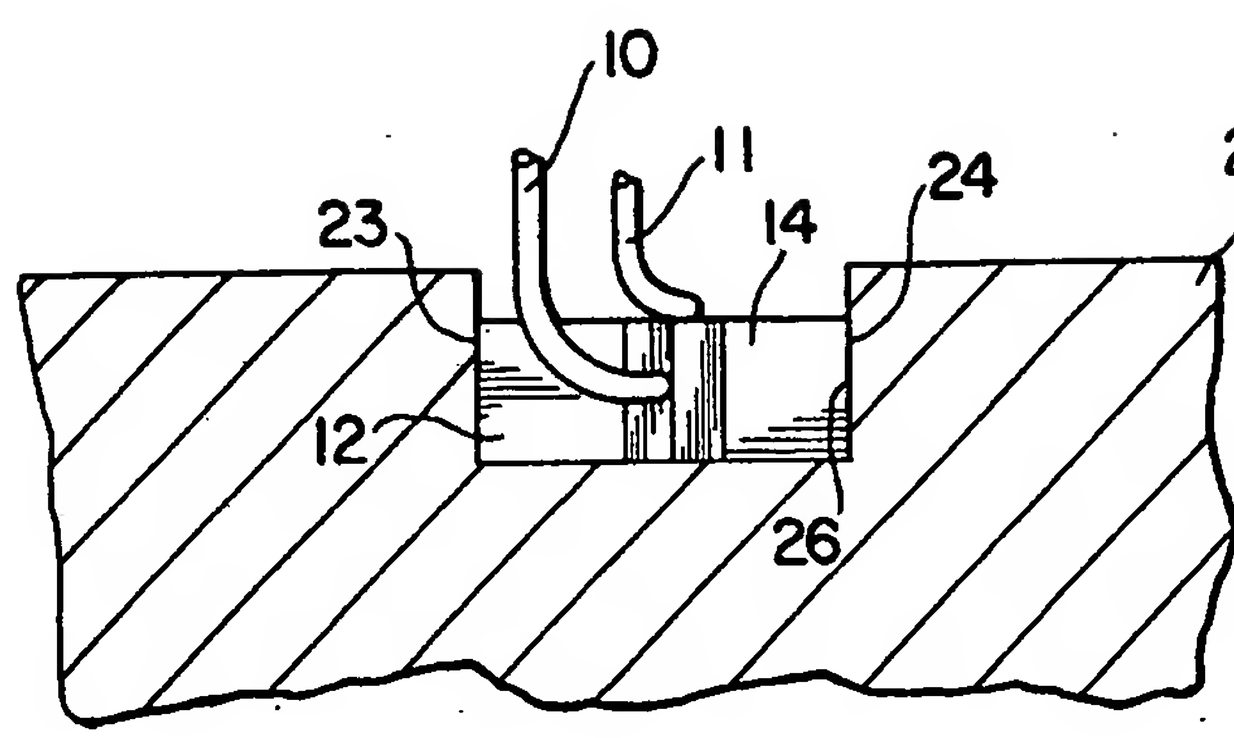

FIG. 6

SPECIFICATION

Strain gauges

This invention relates to strain gauges.

Strain gauges have been developed to measure structural loads to verify proper design of both individual components and an overall structure. Strain gauges now include foil, thin film, or wire resistance devices which are bonded or welded to the test piece to be measured. Loads applied to the test piece can cause it and the bonded gauge to extend, compress, or twist. The resulting strains induced in the gauge change its resistance. If the gauge resistor or resistance forms one leg of a Wheatstone bridge, the bridge will become unbalanced and a voltage will be developed in proportion to the amount of strain induced in the gauge. This approach is the basis of most strain gauge measurements performed today.

Difficulties are encountered when strain measurements are to be made at elevated temperatures. For example, differential expansion between the gauge and test piece induces strain in the gauge, using up a substantial portion of its range and masking the load-induced strain to be measured. Furthermore, for accurate and reliable measurement, resistance strain gauges are generally limited to temperatures below about 315°C (about 600°F). Above this temperature, physical and metallurgical effects such as alloy segregation, phase changes, selective oxidation and diffusion result in large non-repeatable and unpredictable changes in the gauge output, and often in premature failure of the gauge or leadwire system.

Currently, no satisfactory method exists to perform accurate and reliable strain measurements at temperatures exceeding about 315°C. A reliable, stable strain gauge is needed that will work at these elevated temperatures and which will match the thermal expansion of the test piece to enable the gauge to be bonded at low temperatures.

The measurement of the elongation of a structural member such as a long strut presents several problems similar to those encountered in strain measurement. In a relatively benign environment which is free of vibration, the elongation may be slowly varying with time. This situation requires that an elongation sensor be capable of essentially *d c* measurements. As a consequence, the sensor must exhibit extremely low drift.

This is further complicated when the structural member is in a hostile environment.

Instrumentation for in-flight monitoring of inlet and outlet engine conditions is needed for high-performance aircraft to improve fuel efficiency, engine performance, and overall reliability. This instrumentation must withstand the hostile engine environment which includes high-temperature operating conditions and vibrations. Optical fibres and optical sensing methods have been applied to a number of measurements in hostile environments including displacement, velocity, strain, flow, temperature, particle size distribution, gas composition and fluorescence. These optical sensing methods can also be used to measure pressure in the hostile environment.

Optical sensors can also be designed to operate at high temperatures and in regions of high electromagnetic fields.

According to one aspect of the invention there is provided a strain gauge comprising a pair of plates having facing corrugated surfaces with corrugations of one plate being offset with respect to corrugations of the other plate, a coated optical fibre clamped between the corrugations of the plates for being bent to a greater and lesser extent depending on pressure exerted on the plates for moving the plates together, optical signal applying means connected to one end of the optical fibre for applying an optical signal to the optical fibre, and optical detector means connected to an opposite end of the optical fibre for reading the optical signal and modulations in the optical signal which correspond to pressures applied to the plates, the optical fibre comprising a signal fibre for transmitting the optical signal.

According to another aspect of the present invention there is provided a strain gauge which utilizes a pair of corrugated plates having corrugations that face each other and which are offset with respect to each other, and includes a coated optical fibre engaged between the facing corrugated surfaces and bent by the corrugations by amounts which depend on a biassing force pushing the plates together, whereby light moving through the optical fibre is modulated depending on the amount of pressure applied to the plates.

The strain gauge may include an additional optical fibre which is identical in construction to the first-mentioned optical fibre but which is not engaged between the plates, the second optical fibre being near the first-mentioned optical fibre so as to be exposed to the same temperature condition, light passing through and being modulated by the second optical fibre being used in conjunction with the light passing through and being modulated by the first mentioned optical fibre to produce a thermo-mechanical offset correction value.

By coating a glass optical fibre with aluminium or polyimide, a strain gauge which is useful up to about 427°C (about 800°F) can be obtained. By coating a glass or SiO_2 fibre with gold, the useful temperature range can be expanded up to about 540°C (about 1000°F).

A preferred strain gauge embodying the invention and described hereinbelow is simple in design, rugged in construction and economical

to manufacture, and can withstand severe environmental conditions.

The invention will now be further described, by way of illustrative and non-limiting example, with reference to the accompanying drawings, in which:

Figure 1 is a side view in section showing a strain gauge embodying the present invention in its simplest form, the gauge comprising an optical fibre and a pair of plates;

Figure 2 is a block diagram showing the strain gauge embodying the present invention used with a reference optical fibre in addition to the above-mentioned optical fibre (signal optical fibre);

Figure 3 is a graph plotting load versus displacement for the optical fibre of the strain gauge embodying the invention, the fibre having two spatial bends;

Figure 4 is a graph plotting the strain gauge output voltage versus displacement of the plates of the strain gauge;

Figure 5 is a graph showing calibration of the strain gauge embodying the present invention relative to a reference gauge; and

Figure 6 is a side view in section showing the strain gauge embodying the present invention in a slot formed in a surface of a test piece whose strain is to be measured.

A microbend fibre optic strain gauge (microbend sensor) 1 embodying the invention is shown diagrammatically in Figure 1. The gauge includes a glass-on-glass signal optical fibre 10 having the following nominal characteristics:

Core diameter	125 micrometres;
Clad diameter	170 micrometres;
Numerical aperture	0.2;
Buffer coating	40 micrometres thick aluminium or polyimide; and
Overall diameter	250 micrometres.

Fibres with the above-mentioned coatings are strong and rugged with tensile strengths exceeding 689 MPa (100,000 lbf/in^2). The microbend sensor is a light intensity sensor and, as such, uses simple opto-electronic components. The strain gauge comprises the fibre 10, which is clamped between corrugated plates 12 and 14 made from material identical to that of a test piece. Changes in strain of the test piece change the separation of the plates 12 and 14 and, in turn, the light intensity transmitted at the point of clamping. The corrugation spacing is about 3 mm. Two corrugations 16 are on one plate 12 and three corrugations 18 are on the opposite plate 14 to provide two spatial sinusoidal bends in the fibre 10. The fibre 10 is preloaded (bias compression) between the plates 12 and 14 such that the peak-to-peak fibre bend amplitude is approximately 300 micrometres. In this configuration the sensitivity and repeatability of a microbend sensor has been demonstrated to be 0.006 micrometres. At these preloads the change in corrugated plate displacement with load is very nearly linear, as shown in Figure 3. Also, note from Figure 4 the linearity of the characteristic of the microbend sensor output signal versus displacement of the corrugated plates 12 and 14.

Performance data has been obtained on the microbend fibre optic strain gauge and is shown in Figure 5. The microbend strain gauge was calibrated relative to a reference gauge.

The microbend sensor plates 12 and 14 may be attached to the test piece in several different ways. These include welding or gluing ends 21 and 22 to a surface of the test piece. A less obtrusive method is to form a slot in the surface and insert the plates into the slot. Figure 6 shows a test piece 20 having a slot 26 in which the plates 12 and 14 are engaged. The plates 12 and 14 are urged towards each other by their back or rear surfaces 23 and 24. The method of attachment will be chosen to minimise alterations in the structural properties and static and dynamic response of the test piece.

Accelerated dynamic life tests have been performed on the microbend sensor and have demonstrated a lifetime in excess of one million cycles with peak displacements of 25 micrometres. These tests were performed at 20 kHz cycling frequencies, which also demonstrated the high frequency response capability of the microbend sensor.

The microbend sensor uses inexpensive conventional optoelectronic components including a light emitting diode (LED), shown in Figure 2 at 30, and a silicon photodetector 40. By pulsing the LED and using CMOS integrated circuits to detect and amplify the photodetector signal, an average electronic power drain of less than 12 milliwatts per sensor has been demonstrated.

As described previously and shown in Figure 1, the microbend sensor may be preloaded by bias displacement of the plates 12 and 14 so that the corrugations 16, 18 overlap by an amount greater than or equal to the fibre diameter or maximum expected elongation. When the plates 12 and 14 are heated, the corrugation peak separation with temperature may be calculated. It is also straightforward to show that, for each plate, the change in peak-to-peak corrugation spacing with temperature has a negligible effect on the sensor output signal. It is anticipated in practice that the microbend corrugated plates can be properly aligned so that the corrugation peaks are within + 13 micrometres of the desired preloaded displacement. In this case, the worst thermally induced elongation $(\Delta L)_T$ caused by positioning error is given by:

$$(\Delta L)_T = L\alpha\Delta T$$

Substituting for ΔT the required thermal operating range of 400°C, for α a value of 8.5 $\times 10^{-6}/°C$ for a typical titanium alloy, and for L the position error of 13 micrometres, the thermally induced elongation error is:

$(\Delta L) = (13)(8.5 \times 10^{-6})(400) = 0.04$ micrometres.

Thus, for a gauge length of lcm, the resulting thermally induced error is (4μ) strain, where 1μ strain $= 1\mu m/m$.

In addition to compensation of the thermomechanical offset just described, changes in optical fibre light transmission can be compensated as well as changes in light source intensity and drift of photodetector output sensitivity. Success in compensating for these changes has been achieved by using an approach shown diagrammatically in Figure 2. As shown in Figure 2, a second optical fibre (reference fibre) is co-located with the signal optical fibre 10 clamped between the corrugated plates (not shown in Figure 2). The reference optical fibre 11 is unclamped, but sees the same thermal environment along its length as the signal fibre 10.

Both the signal and reference fibres 10 and 11 are connected through known optical splices 42 to a fibre optic coupler 44. The light output from the LED 30 is split into two parts by a 3 dB coupler 44, and the split output is coupled through the splicers 42 to the signal fibre 10 and to the reference fibre 11. The optical fibres 10 and 11, which are multimode optical fibres, supply output signals to the photodetector 40, which is a dual photodetector, and output converter circuitry 46 associated therewith. Signals A and B are digitised and converted in the convertering circuit 46 to form values $(A-B)/(A+B)$ for the compensated sensor signal.

A major advantage of the microbend strain gauge embodying the invention is that it allows matching of the thermal expansion coefficient of the plates 12 and 14 with that of the substrate material to be tested. This cannot be done with conventional strain gauges, such as resistance strain gauges, and has the effect of (1) improving the range at temperature and (2) reducing the thermal output of the gauge.

The test data shown in Figures 3 to 5 was obtained using stainless steel plates 12 and 14. In general, the plate material would be chosen to match the thermal expansion coefficient of the underlying material. As an alternative, if the predominant strain direction is known, the thermal expansion coefficients of the plates and substrate can be initially mismatched, i.e. biassed against one another so as to increase the range of the strain gauge while maintaining the same sensitivity.

The plates 12 and 14 can also be made of fused silica or other similar ceramics to increase resistance to thermal effects such as thermal degrading of the plates and the thermal expansion and contraction effect.

Advantages of the microbend fibre optic strain gauge embodying the invention are as follows:

(i) Operating temperatures above 427°C (800°F).

(ii) Lightweight, compact and non-obtrusive, especially if a structural member or other test piece is slotted to accept the corrugated microbend sensor plates.

(iii) Accuracy of 0.005 micrometres at frequencies from d c to 20 kHz.

(iv) The microbend sensor may be mechanically and electronically compensated with temperature, and electronic signal processing may be used to eliminate drift.

(v) Compatible with composite and metallic materials, this requirement being met by making the corrugated microbend sensor plates from material identical to the material of a strut or other test piece.

(vi) Immune to electromagnetic interference and electromagnetic pulses.

(vii) Since the sensor uses non-polarised light energy to operate, spark hazards are non-existent, and remote mounted sensors are locatable in explosion hazard environments.

(viii) Inert glass optical fibre material is resistant to corrosion.

To increase the useful range of the strain gauge up to about 540°C (about 1,000°F), a gold coated SiO_2 optical fibre can be utilised in place of the aluminium or polyimide coated glass fibre. Both the signal fibre 10 and reference fibre 11 can be constructed in this way. A strain gauge embodying the invention and having this temperature resistance can be useful for long-term measurements of creep strains on reheat or main steam lines in boilers.

Field installation of such gauges can be effected by capacitive discharge spot welding, thus requiring only local descaling and grinding for surface preparation. Insulation which is normally used over pipes to be fitted with the strain gauge need only be removed in the immediate area of the gauge. A plug of insulation which is, for example, 50 to 75 mm (two to three inches) in diameter, could be removed, the gauge installed, and the plug replaced. The optical fibre leads would be brought out through the insulation at the plug for connection to extension fibres and strain readout equipment.

CLAIMS

1. A strain gauge comprising a pair of plates having facing corrugated surfaces with corrugations of one plate being offset with respect to corrugations of the other plate, a coated optical fibre clamped between the corrugations of the plates for being bent to a

greater and lesser extent depending on pressure exerted on the plates for moving the plates together, optical signal applying means connected to one end of the optical fibre for applying an optical signal to the optical fibre, and optical detector means connected to an opposite end of the optical fibre for reading the optical signal and modulations in the optical signal which correspond to pressures applied to the plates, the optical fibre comprising a signal fibre for transmitting the optical signal.

2. A strain gauge according to claim 1, wherein the optical fibre is coated with one of aluminium, polyimide and gold.

3. A strain gauge according to claim 1 or claim 2, wherein the optical fibre has a core of glass or Sio_2.

4. A strain gauge according to claim 1, including a reference fibre connected between the optical signal applying means and the optical detector means and having a portion in the vicinity of the plates for being exposed to the same thermal condition as bent areas of the signal fibre which is clamped between the plates.

5. A strain gauge according to claim 4, wherein the optical signal applying means comprises a light source and a fibre optic coupler for splitting light from the light source into equal optical signals which are applied to the reference and signal fibres.

6. A strain gauge according to claim 4 or claim 5, wherein the signal and reference fibres have a glass core and cladding and an aluminium coating.

7. A strain gauge according to claim 4 or claim 5, wherein the signal and reference fibres have a glass core and cladding and a polyimide coating.

8. A strain gauge according to claim 4 or claim 5, wherein the signal and reference fibres have a core of SiO_2 and a coating of gold.

9. A strain gauge according to any one of the preceding claims, wherein the plates are made from a material having a temperature expansion coefficient similar to that of any material to be tested by the strain gauge.

10. A strain gauge substantially as herein described with reference to Figure 1 of the accompanying drawings.

11. A strain gauge substantially as herein described with reference to Figure 2 of the accompanying drawings.

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